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# Biomass downdraft gasifier with internal cyclonic combustion chamber: Design, construction, and experimental results

Krushna Patil<sup>\*</sup>, Prakash Bhoi, Raymond Huhnke, Danielle Bellmer

Biosystems & Agricultural Engineering Department, Oklahoma State University, Stillwater, OK 74078, USA

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## ABSTRACT

An exploratory downdraft gasifier design with unique biomass pyrolysis and tar cracking mechanism is evolved at Oklahoma State University. This design has an internal separate combustion section where turbulent, swirling high-temperature combustion flows are generated. A series of research trials were conducted using wood shavings as the gasifier feedstock. Maximum tar cracking temperatures were above 1100 °C. Average volumetric concentration levels of major combustible components in the product gas were 22% CO and 11% H<sub>2</sub>. Hot and cold gas efficiencies were 72% and 66%, respectively.

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## 1. Introduction

Gasification process offers significant potential to convert biomass materials into energy fuels and chemicals. Production of ethanol from biomass through a gasification–fermentation route is one of the major on-going research programs at Oklahoma State University, Stillwater. One of the aims of the gasification research is to evaluate different biomass gasifier designs to generate producer gas high in carbon monoxide and hydrogen and low in tar and other impurities. The gasifier designs included: an atmospheric air-based bubbling fluidized bed, a cyclonic entrained flow and a fixed bed downdraft type system.

Gumz (1950) provided wall tuyeres in updraft gasifier to create a hot zone for cracking of tar compounds, but generation of cold spots between the tuyeres and un-even temperature distribution in the hot zone was observed. Susanto et al. (1982) studied a gasifier with an internal recycle of pyrolysis gas. Air was introduced through a pipe with an injector unit for suction of the gas. The pyrolysis gas–air mixture was combusted in a combustor mounted on the rotating ash grate. Recycle ratio (recycled gas flow rate/air flow rate) in the range of 0.4–1.6 resulted in stable combustion of recycled gas. It was also observed that tar was significantly reduced. Kaupp and Goss (1984) described the De Lacotte gas producer system that burned pyrolysis gases in a separate combustor

to obtain tar free gas. The resulting non-condensable gas stream was then expelled in the main reactor. Kurkela (1989) investigated the cracking of updraft gas generated using peat and biomass as the feedstocks. The 200 °C raw gas was piped to a separate cracking reactor where preheated air at 400 °C was introduced to the upper zone. When the cracking air was increased, the absolute gas composition increased up to a certain stage while the tar content decreased significantly.

Considering the fact that the cyclone type of reactor generates producer gas with as much as five times less alkali-based impurities (Gabra et al., 2001) compared to a bubbling-type fluidized bed gasifier, first generation cyclone gasifier system was designed and tested using wood powder as the fuel (Patil et al., 2004). Producer gas generated from this gasifier ranged from 16% to 20% CO, 4.2% to 6% H<sub>2</sub> and 3.2% to 4% CH<sub>4</sub> on a volume basis. However, this gasifier also generated high amounts of char residue up to 20% by weight of the input biomass resulting in reduced biomass conversion efficiency. To overcome this problem, a second generation cyclone-based downdraft gasifier system was designed and implemented (Patil et al., 2005). The main components of the downdraft gasifier included a cyclone-based pyrolysis section followed by a fixed-bed gasification section located at the bottom of the gasifier. This gasifier system was subjected to extensive trials using wood shavings, and corn fermentation wastes. Even though the gasifier system performance was improved, i.e. better char conversion, higher H<sub>2</sub> and CO concentrations, and reduced impurities in the producer gas, the pyrolysis section remained relatively inactive because of low temperatures. As a result, biomass was not completely pyrolyzed before reaching the fixed bed gasification chamber.

<sup>\*</sup> Corresponding author. Tel.: +1 405 7448418; fax: +1 405 7446059.

E-mail addresses: [krushna.n.patil@okstate.edu](mailto:krushna.n.patil@okstate.edu) (K. Patil), [prakash.bhoi@okstate.edu](mailto:prakash.bhoi@okstate.edu) (P. Bhoi), [raymond.huhnke@okstate.edu](mailto:raymond.huhnke@okstate.edu) (R. Huhnke), [danielle.bellmer@okstate.edu](mailto:danielle.bellmer@okstate.edu) (D. Bellmer).

Based on the reviewed literature, and the results of the cyclone-based downdraft gasification studies by Patil et al. (2005), a series of reactor configurations were tested and evaluated to maximize concentration levels for the major combustible components like CO and H<sub>2</sub> in the product gas and minimize gas tars and particulate content. In 2006, the first prototype of the downdraft gasifier design evolved (Patil et al., 2006). In this design, an internal separate combustion section generates turbulent, swirling high-temperature combustion flows. High temperatures in the cyclonic section facilitate biomass pyrolysis. Combustion products from the cyclonic section pass through a char gasification chamber where additional tar cracking takes place. This paper outlines the design and construction of the downdraft gasifier system, and the gasification results obtained for wood shavings.

## 2. Methods

### 2.1. Biomass feedstock

Wood shaving material supplied by the Shutter Mill, Inc., Stillwater, OK was used as the feedstock. Proximate and ultimate analyses were performed by Hazen Research Inc., Golden, CO. For bulk density determination, the material was poured into a 473-ml container (One pint model, OHAUS Corp., Pine Brook, NJ) from 100 mm above the container and weighed. The bulk density of 94 kg/m<sup>3</sup> was determined by dividing the weight of the material by the container volume. The proximate analysis revealed the moisture content, volatile matter, fixed carbon and ash content of 5.30%, 87.83%, 11.74%, and 0.43% (dry basis), respectively. The ultimate analysis results (dry basis) indicated the carbon, hydrogen, oxygen, nitrogen, and sulfur content of 50.47%, 5.74%, 43.32%, 0.03%, and 0.01%, respectively. The lower heating value (dry basis) of 18.03 MJ/kg was observed for the wood shaving feedstock material.

### 2.2. Gasifier design and test facility

The major components of the experimental set up, shown in Fig. 1, are the biomass feeding unit and the gasification reactor. Biomass feeding unit consists of a biomass hopper (1), air lock valve (2) and two screw feeders (3). The gasification reactor consists of a biomass section (4) at the top, pyrolysis and tar cracking (PTC) zone (5) in the middle and the char gasification section (6) at the bottom. PTC zone consists of a twin cylinder unit extended downward to the top of the gasification section with an annular space in between the cylinders. The inner cylinder is perforated and holds the biomass column. For initial firing, propane gas (7) is supplied at the top of the PTC section. An air compressor (8) supplies air for gasification and a mass flow meter (9) (model 810 M-DR-13 Sierra Instruments, Inc., Monterey, California) measures input air flow rate. An electrical air heater (10) (Model AHF 14240 Omega Engineering, Stamford, CT) provides capability to evaluate preheated air as the gasifying agent.

The tar-loaded pyrolysis gases enter into the annular space of the PTC. Gasifying air is tangentially mixed with the pyrolysis gases. Turbulent and high temperature swirling combustion flows are generated where tar cracking occurs. High temperatures in the annular space of PTC also facilitate biomass pyrolysis. The high temperature combustion products become components in subsequent reactions that occur in the char gasification section. A perforated grate (11) at the bottom of the char gasification section is used to support the bed material. Biomass ash falls into the ash chamber (12) while the gas is piped to a cyclone separator (13) where particulates are removed. On the downstream side, a tar and particulate measurement system (14) is attached. It was developed in-house (Cateni, 2007) based on the international standards

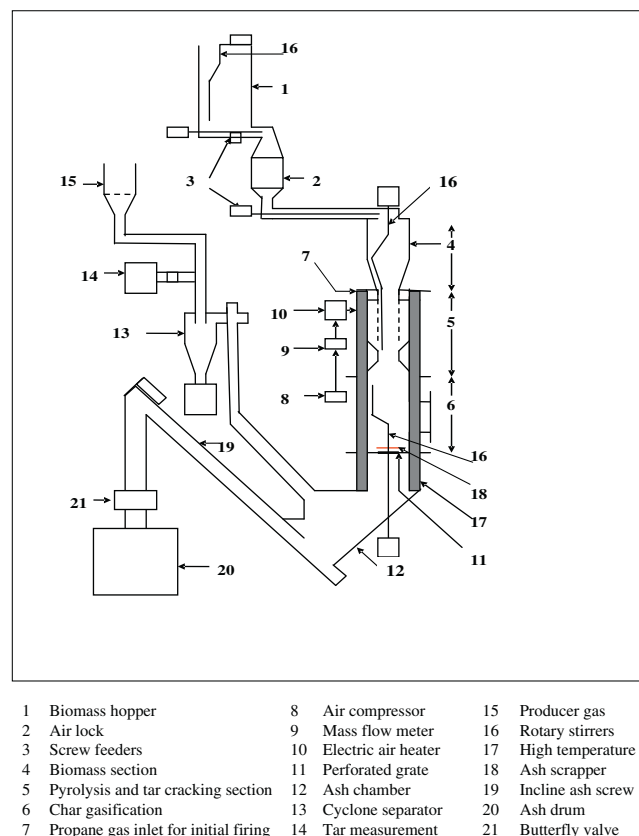


Fig. 1. Schematics of the experimental set-up.

for tar and particulate measurement. A gas chromatograph (Model CP-3800, Varian, Inc., Palo Alto, CA) is used for producer gas analysis. Exhaust gases are subsequently flared (15). Three rotary stirrers (16) facilitate material flow. High temperature refractory (17) lines inside of the gasification reactor. A rotating 4-armed ash scrapper (18) is used to unload ash from the reactor and an inclined ash screw conveyor (19) to transport the ash into the ash drum (20). While manually unloading the ash from the ash drum (20) during the gasifier operation, the butterfly valve (21) is closed to isolate ash drum from gasifier's producer gas stream. LabView (National Instruments, USA) is used to monitor and record the data. An Oxygen Bomb calorimeter (6200 Parr Instrument, Moline IL) was used to analyze solid residues (char & ash) for high heating values. The gasification reactor, gas pipes, and cyclone separator are insulated with a 25-mm thick ceramic wool blanket. Type-K thermocouples are used for temperature measurements.

### 2.3. Test procedure and calculations

Test preparation started by loading 5 kg of wood charcoal onto the grate. The gasification reactor was then completely filled with biomass of known weight. The gasifier was preheated using propane for about 10 min. When the temperature in the annular space of the PTC reached approximately 600 °C, preheating was discontinued. The desired air flow was then set. Within minutes, the reactor temperature profile stabilized. During each test, biomass fuel level in the gasification reactor was maintained by intermittently operating the biomass feeding system. Reactor temperature profile, temperatures of the producer gas at the exit of the cyclone and that of the flame, pressure drops across the gasification reactor and the entire system, input air flow rate, and quantity of biomass loaded before and during the tests were closely monitored. The minimum

duration of each gasification test was 3 h. Producer gas sampling began when the system stabilized as indicated by the reactor temperature profile. For gas analysis, samples were taken every 10–15 min to determine the variation of gas composition with time. The gas flow rate was determined by nitrogen balance. The gas calorific values were determined using the volumetric gas composition values from gas chromatograph and the theoretical heating values of all the combustible components. Producer gas tar content was measured for selected gasification tests. At the end of each experiment, mass and energy balance calculations were performed to estimate the accuracy of measurements.

Based on the published literature (Kaupp and Goss, 1984), specific air input rate (SAIR), specific gasification rate (SGR), cold gas & hot gas efficiencies (CGE and HGE), and mass & energy balance (MB and EB) were calculated as follows:

$$\text{SAIR} = \frac{\text{IAFR}}{\text{RCAOZ}} \quad (1)$$

where SAIR, specific air input rate, kg of air/h-m<sup>2</sup>; IAFR, input air flow rate, kg/h; RCAOZ, reactor's cross sectional area in oxidation zone, m<sup>2</sup>

$$\text{SGR} = \frac{\text{DGFR}}{\text{RCAOZ}} \quad (2)$$

where SGR, specific gasification rate, cu. m dry gas/h-m<sup>2</sup>; DGFR, dry gas flow rate, m<sup>3</sup>/h; RCAOZ, reactor's cross sectional area in oxidation zone, m<sup>2</sup>

$$\text{HGE} = \frac{\text{PCSE}}{\text{DBEIN} + \text{ASEIN}} \times 100 \quad (3)$$

where HGE, hot gas efficiency, %; PCSE, producer gas chemical and sensible energy output rate, MJ/h; DBEIN, Dry biomass energy input rate, MJ/h; ASEIN, Air sensible energy Input rate, MJ/h

$$\text{CGE} = \frac{\text{PGSE}}{\text{DBEIN} + \text{ASEIN}} \times 100 \quad (4)$$

where CGE, Cold gas efficiency, %; PGCE, producer gas chemical energy output rate, MJ/h; DBEIN, Dry biomass energy input rate, MJ/h; ASEIN, air sensible energy Input rate, MJ/h

$$\text{MB} = \frac{\text{TMOUT}}{\text{TMIN}} \times 100 \quad (5)$$

where MB, Mass balance, %; TMOUT, Total mass output rate, kg/h; TMIN, Total mass input rate, kg/h

$$\text{EB} = \frac{\text{TEOUT}}{\text{TEIN}} \times 100 \quad (6)$$

where EB, Energy balance, %; TEOUT, Total energy output rate, MJ/h; TEIN, Total energy input rate, MJ/h

### 3. Results and discussion

Table 1 summarizes average gasifier operation and performance data at maximum efficiency conditions for wood shavings. The levels of specific air input rate (SAIR) evaluated are 437, 472, 490, 542, and 594 kg of air/h-m<sup>2</sup>. The effects of SAIR on gasifier temperature profile, gas composition, gas yield, gasifier efficiencies and mass and energy balance are discussed in the following sections. Tar in the raw producer gas at the exit of the gasifier was measured at maximum efficiency condition.

#### 3.1. Gasifier temperatures

Tar cracking temperatures (TCT), reactor bed temperature above the grate (TAG), producer gas temperature at the gasifier exit (TGexit), and the producer gas flame temperatures (TGF) are

**Table 1**

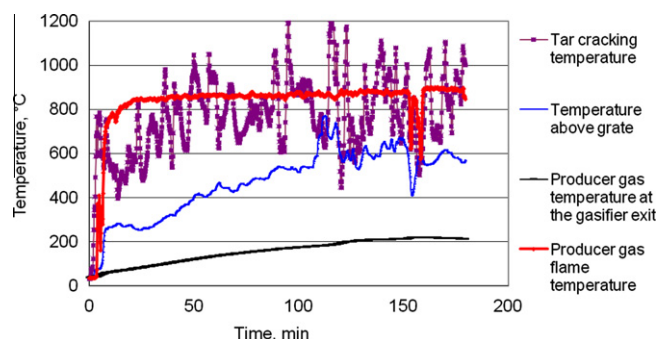
Gasifier operation and performance data at maximum efficiency conditions.

	Wood shavings
Specific air input rate, kg of air/h-m <sup>2</sup> kg of air/h-sq. m	542
Fuel feed rate (ave.), kg/h	18.7
Input air temperature (ave.), °C	38 ± 4.0
Specific gasification rate, m <sup>3</sup> of dry gas/h-sq. m	666
Tar cracking zone temperature, TCT, (ave.), °C	814 ± 148
TCT (max.), °C	1223
Flame temperature (ave.), °C	866 ± 38
Flame temperature (max.), °C	901
Pressure drop across gasifier, inch of water	11.0 ± 2.3
<i>Major gas Components, % vol.</i>	
CO	22.2 ± 1.7
H <sub>2</sub>	10.9 ± 2.0
CH <sub>4</sub>	4.5 ± 0.6
CO <sub>2</sub>	11.5 ± 2.0
N <sub>2</sub>	50.0 ± 2.4
LHV gas (MJ/Nm <sup>3</sup> )	6.1 ± 0.41
Dry gas yield (Nm <sup>3</sup> /kg)	1.5 ± 0.1
Tar content, g/Nm <sup>3</sup>	48 ± 6.4
Hot gas efficiency, %	72.7 ± 6.9
Cold gas efficiency, %	66.7 ± 6.7
Mass balance, %	90.7 ± 3.1
Energy balance, %	80.7 ± 4.9

among the prime temperature data reflecting on the gasifier performance. TCT, TGexit and TGF values at maximum efficiency conditions were 814, 200 and 866 °C, respectively. A typical curve showing variation in temperature profiles with time is depicted in Fig. 2. Note that, the gasifier temperature profile stabilized within 60 min from the system start time. Fluctuations in the reactor temperatures were observed because of low bulk density of wood shavings.

As the SAIR increased from 437 to 594 kg of air/h-m<sup>2</sup>, variations in tar cracking temperatures (TCT), reactor bed temperatures above the grate (TAG), producer gas temperatures at the gasifier exit (TGexit), and the producer gas flame temperatures (TGF) were 732–917, 462–561, 150–189 and 855–873 °C, respectively. Up to SAIR of 542 kg of air/h-m<sup>2</sup>, the increase in TCT and TAG temperatures were 11% and 13%, respectively, and thereafter remained constant. Increase in the TGexit temperature was only 5%. The direct relationship observed between SAIR and reactor temperatures TCT, TAG and TGE is due to the fact that as the SAIR level increases, more oxygen becomes available per unit amount of the biomass fuel in the combustion zone which results in an increase in gasification temperatures. Constant flame temperatures indicate stable gas quality in terms of gas composition throughout the tested range of SAIR.

The gasifier temperature data is quite comparable to the published literature (Table 2) on tar cracking temperatures in the



**Fig. 2.** Variations in gasifier temperatures with time [specific air input rate: 542 kg of air/h-m<sup>2</sup>; biomass input rate: 18.7 kg/h; average input air temperature: 38 °C].

**Table 2**

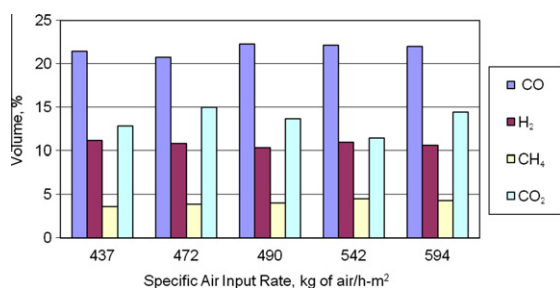
Effect of SAIR on dry gas yield, lower heating value of syngas, hot and cold gas efficiencies, and mass and energy balance values.

Specific air input rate, kg/h-m <sup>2</sup>	420	437	472	490	542	594
Dry gas yield, kg of dry gas/kg of dry biomass	1.1	1.3	1.0	1.2	1.5	1.2
Lower heating value, MJ/m <sup>3</sup>	5.4	5.5	5.4	5.9	6.1	6.0
Hot gas efficiency, %	54.1	52.7	50.0	57.2	72.7	57.0
Cold gas efficiency, %	49.6	48.4	45.1	52.5	66.7	52.6
Mass balance, %	83.9	84.2	81.6	86.2	90.7	87.0
Energy balance, %	70.3	66.3	73.2	70.7	80.7	69.7

downdraft gasifiers (Zainal et al., 2002; Dogru et al., 2002a,b, Sheth and Babu, 2009, 2010, Sharma, 2009, 2011, Erlich and Fransson, 2011).

### 3.2. Gas composition

The volumetric percentage of the major producer gas constituents detected for maximum efficiency conditions obtained at the SAIR level of 542 kg of air/h-m<sup>2</sup> are given in Table 1. Variations in volumetric concentration levels for CO, H<sub>2</sub>, CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> were 20.8–23.6%, 8.7–13.2%, 3.6–5.2%, 9.3–14.5% and 47.2–53.6%, respectively. It was observed that within 1 h from the start of the gasifier, the concentration levels of all the gases stabilized and remains throughout the test period. At the beginning when the gasifier temperature profile was close to becoming stabilize (55 min from the start), the volumetric concentration levels for CO, H<sub>2</sub> and CO<sub>2</sub> in the producer gas were 20.1%, 11% and 14.5%, respectively. Increase in CO level (23.6%), and decrease in both H<sub>2</sub> and CO<sub>2</sub> levels (9.4% and 12.2%, respectively) within the next



**Fig. 3.** Effect of specific air input rate on the concentration of major producer gas constituents.

**Table 3**

Gasifier performance comparison with published data on conventional downdraft gasification systems.

Feedstock	ER <sup>a</sup>	Tar cracking temperature, °C	Calorific value, MJ/Nm <sup>3</sup>	CO, Volume%	H <sub>2</sub> , Volume%	Gas tar at the gasifier exit, g/Nm <sup>3</sup>	Reference
Wood Shavings	0.20	800	6.1	22	11	48	This study (Table 1)
Furniture wood and wood chips	0.38	1000	5.3	24	14	–	Zainal et al. (2002)
Hazelnut shells	0.27	1050	5.0	21	13.1	3.0	Dogru et al. (2002a)
Sewage sludge	0.40	1077	3.8	10.6	10.9	6.26	Dogru et al. (2002b)
Wood waste	0.21	1050	6.3	22	12	–	Sheth and Babu (2009)
Kiker (Acacia wood)	–	895	4.2	22	12	–	Sharma (2009)
Waste wood	0.21	900	6.3	22	12	–	Sheth and Babu (2010)
Wood pellet, Bagasse pellet Empty fruit bunch pellet	0.23–0.43	700–1200	4.1–5.4	17–25.7	9.9–13.5	–	Erlich and Fransson (2011)
Hardwood	–	927	3.5–4.0	19–23	11–13	–	Sharma (2011)

<sup>a</sup> ER: Equivalence ratio, =the actual air–fuel ratio/the air–fuel ratio for complete combustion.

30 min is the result of the Boudouard Reaction ( $C + CO_2 \leftrightarrow 2CO$ ,  $\Delta H = 173$  MJ/kg mol). Thereafter, during the remainder of the test, CO remains constant, while H<sub>2</sub> increased to about 13% and CO<sub>2</sub> decreased to 9.3%. This is due to the water gas (WG) reaction ( $C + H_2O \leftrightarrow CO + H_2$ ,  $\Delta H = 131$  MJ/kg mol), and water gas shift (WGS) reaction ( $CO + H_2O \leftrightarrow H_2 + CO_2$ ,  $\Delta H = -41$  MJ/kg mol). CH<sub>4</sub> was about 5% throughout the test except 3.65% at about 80 min from the start. This may be due to the possibility of the momentary prominence of methane reforming reaction, ( $CH_4 + H_2O \leftrightarrow 3H_2 + CO$ ,  $\Delta H = 206$  MJ/kg mol).

The effect of SAIR on the volumetric percentage of major gas constituents in the producer gas is shown in Fig. 3. It reveals that throughout the operating range of SAIR (437–594 kg of air/h-m<sup>2</sup>), the CO and H<sub>2</sub> concentration levels remained approximately 22% and 11%, respectively. Maximums for both CO and H<sub>2</sub> concentrations and minimum for CO<sub>2</sub> concentration levels were observed at SAIR level of 542 kg of air/h-m<sup>2</sup> (Boudouard Reaction). CH<sub>4</sub> concentration level ranged from 4% to 4.5%.

The gas composition results align with the published data given in Table 3. It reveals CO: 11–24 volume%, while H<sub>2</sub>: 11–14 volume% with maximum values for wood materials (Zainal et al., 2002), while minimum for sewage sludge (Dogru et al., 2002b).

### 3.3. Producer gas calorific value and tar

The variation of producer gas lower heating value with SAIR is given in Table 2. The highest lower heating value of 6.1 MJ/m<sup>3</sup> was observed at SAIR of 542 kg of air/h-m<sup>2</sup>. The results are in agreement with the published findings from other biomass downdraft gasification studies as shown in Table 3. The average producer gas tar content value of 48 g/Nm<sup>3</sup> was observed in this study. The published producer gas tar values for the throat type downdraft gasifiers, reported by Dogru et al., 2002a,b are quite low: Hazelnut shells-3 g/Nm<sup>3</sup> and Sewage sludge-6.3 g/Nm<sup>3</sup>. One of the major reasons for the high level of producer gas tar content in the present study is the throat-less nature of the gasifier design. Secondly, the fluffy nature of and comparatively low fixed carbon content in the wood shavings material which was used as the gasifier feedstock. It resulted in comparatively lower combustion zone temperatures of around 800 °C coupled with higher value for producer gas tar content. Another major reason for wide difference between the producer gas tar values obtained in this study and the ones reported by other researchers (Table 2) is use of entirely different experimental tar measurement setups. As mentioned earlier in the Section 2.2, the tar setup used in this study was based on the international standards for tar and particulate measurement (Catani, 2007).



### 3.4. Dry gas yield and gasifier efficiencies

The dry gas yield, a ratio of the flow rate of the dry gas exiting the gasifier and the dry biomass supplied to the gasifier, is given in Table 2. As the SAIR increased from 437 to 594 kg of air/h-m<sup>2</sup>, the dry gas yield varied from 1.2 to 1.5 kg of dry gas per kg of dry biomass, with maximum found at 542 kg of air/h-m<sup>2</sup>. With increase in SAIR, oxygen availability per unit biomass increases and more conversion of biomass char into gas takes place. The maximum gasifier efficiency data is shown in Table 1, while variations in both, hot gas and cold gas efficiencies with SAIR are shown in Table 2. Hot gas efficiency varied between 50% and 73%, while cold gas efficiency between 45% and 67%. The highest values (Hot gas: 73% and Cold gas: 67%) were observed at the SAIR level of 542 kg of air/h-m<sup>2</sup>. It is because the maximums for producer gas calorific values and the dry gas yield were also observed at the same SAIR level of 542 kg of air/h-m<sup>2</sup>. Producer gas calorific value and the dry gas yield have direct correlation with the gasifier efficiencies.

### 3.5. Mass and energy balance

The mass and energy balance results are presented in Tables 1 and 2. Mass balance values vary between 82% and 91% while energy balance values between 71% and 81%. Deviation from 100% in mass balance reflects on the cumulative effect of practical difficulties faced in quantifying all tars, outgoing water components, and solid residues at the end of experiments, and also possible errors in measurements of all inputs and outputs. Energy balance values have been calculated based on mass inputs and outputs and respective heat content values. Discrepancies in mass balance closure values got reflected into the energy balance closure values. Discrepancies in energy balance closure values can also be explained by possible heat losses from the hot surfaces of the gasifier system.

## 4. Conclusions

Downdraft biomass gasifier design with an internal cyclonic combustion chamber developed under this study showed consistent performance in tar cracking temperatures, volumetric gas concentration levels for CO and H<sub>2</sub>, and gasifier efficiencies. Gasification tests using wood shavings showed average hot gas and cold gas efficiencies of 73% and 67%, respectively, at the specific air input rate of 542 kg of air/h-m<sup>2</sup>. Maximum tar cracking temperatures were above 1100 °C.

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## References

- Cateni, B. 2007. Effects of feed composition and gasification parameters on Producer gas from a pilot scale fluidized bed gasifier. Unpublished PhD thesis. Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK.
- Dogru, M., Howarth, C.R., Akay, G., Keskinler, B., Malik, A.A., 2002a. Gasification of Hazelnut shells in a downdraft gasifier. *Energy* 27, 415–427.
- Dogru, M., Midilli, A., Howarth, C.R., 2002b. Gasification of sewage sludge using a throated downdraft gasifier and uncertainty analysis. *Fuel Processing Technology* 75, 55–82.
- Erlich, C., Fransson, T.H., 2011. Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study. *Applied Energy* 88, 899–908.
- Gabra, M., Petterson, E., Beckman, R., Kjellstrom, B., 2001. Evaluation of cyclone gasifier performance for gasification of sugar cane residue – Part I: gasification of bagasse. *Biomass and Bioenergy* 21, 351–369.
- Gumz, W., 1950. *Producers and Blast Furnaces*. John Wiley and Sons, New York.
- Kaupp, A., Goss, J.R., 1984. *Small Scale Gas Producer Engine Systems*. US Agency for International Development, Washington, DC.
- Kurkela, E., 1989. Status of peat and biomass gasification in Finland. *Biomass* 18 (3–4), 287–292.
- Patil, K.N., Bowser, T.J., Bellmer, D.D., Huhnke, R.L., 2004. Design, development, testing and evaluation of a laboratory cyclone gasification system. Poster presented at ASAE Annual International meeting, Ottawa, Canada.
- Patil, K.N., Huhnke, R.L., Bellmer, D.D., Bowser, T.J., 2005. Design of a new cyclone based downdraft gasification system. Poster presented at ASAE Annual International meeting, Tampa, Florida.
- Patil, K.N., Huhnke, R.L., Bellmer, D.D., 2006. Performance of a unique downdraft gasifier. Paper number 066030. Paper presented at ASABE Annual International meeting, Portland, Oregon.
- Sharma, A.K., 2009. Experimental study on 75 kWth downdraft (biomass) gasifier system. *Renewable Energy* 34, 1726–1733.
- Sharma, A.K., 2011. Modeling and simulation of a downdraft biomass gasifier 1. Model development and validation. *Energy Conversion and Management* 52, 1386–1396.
- Sheth, P.N., Babu, B.V., 2009. Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier. *Bioresour. Technology* 100, 3127–3133.
- Sheth, P.N., Babu, B.V., 2010. Production of hydrogen energy through biomass (wood waste) gasification. *Journal of Hydrogen Energy* doi: 10.1016/j.ijhydene.2010.03.009.
- Susanto, H., Beenackers, A.A.C.M., Swaaij W.P.M.Van., 1982. Moving bed gasifier with internal recycle of pyrolysis gas, in: *Proceeding of the Second EC conference on Energy from Biomass*, Berlin.
- Zainal, Z.A., Rifau, Ali., Quadir, G.A., Seetharamu, K.N., 2002. Experimental investigation of a downdraft gasifier. *Biomass and Bioenergy* 23, 283–289.